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Chuang et al.

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(54) **CONTROL METHOD FOR CONTROLLING A CURRENT VECTOR CONTROLLED SYNCHRONOUS RELUCTANCE MOTOR**

(71) Applicant: **NATIONAL CHENG KUNG UNIVERSITY**, Tainan (TW)

(72) Inventors: **Tzu-Shien Chuang**, Hsinchu (TW); **Mi-Ching Tsai**, Tainan (TW); **Min-Fu Hsieh**, Tainan (TW)

(73) Assignee: **NATIONAL CHENG KUNG UNIVERSITY**, Tainan (TW)

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H02P 6/00	(2006.01)
H02K 19/10	(2006.01)
H02P 21/14	(2006.01)

(52) **U.S. Cl.**

CPC ***H02P 21/0096*** (2013.01); ***H02K 19/103*** (2013.01); *H02P 21/0035* (2013.01); *H02P 21/146* (2013.01); *Y02T 10/643* (2013.01)

(58) **Field of Classification Search**

CPC .. B62D 5/046; B62D 5/0463; H02P 21/0035; H02P 21/0096; G01R 33/3453; H02K 3/28; H02K 19/103; Y02T 10/643

USPC 318/400.02, 400.01, 362, 364, 365; 307/151; 363/1–12

See application file for complete search history.

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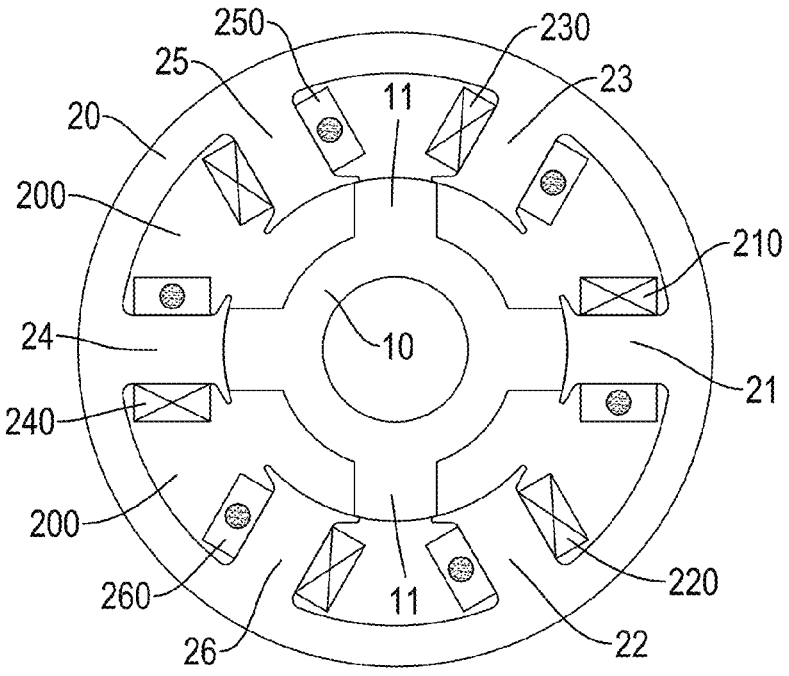
Primary Examiner — Bentsu Ro
Assistant Examiner — Zemenay Truneh
(74) *Attorney, Agent, or Firm* — patenttm.us

(57) **ABSTRACT**

A current vector controlled synchronous reluctance motor and control method thereof, wherein the motor has a coil on each of the teeth. The coils form a U-phase winding, a V-phase winding and a W-phase winding. The phase windings receive a balanced three-phase current vector to induce closed magnetic field lines, such that the coils induce same magnetic poles adjacent to the rotor unit. Two short magnetic routes are formed along three adjacent teeth and the rotor unit. The efficiency of the reluctance motor is high.

3 Claims, 15 Drawing Sheets



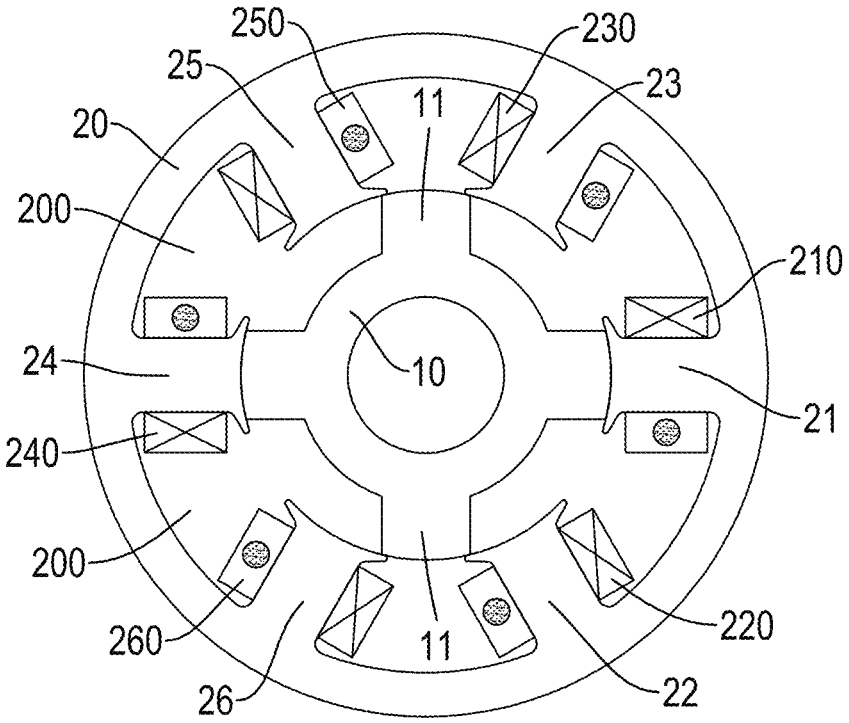


FIG.1

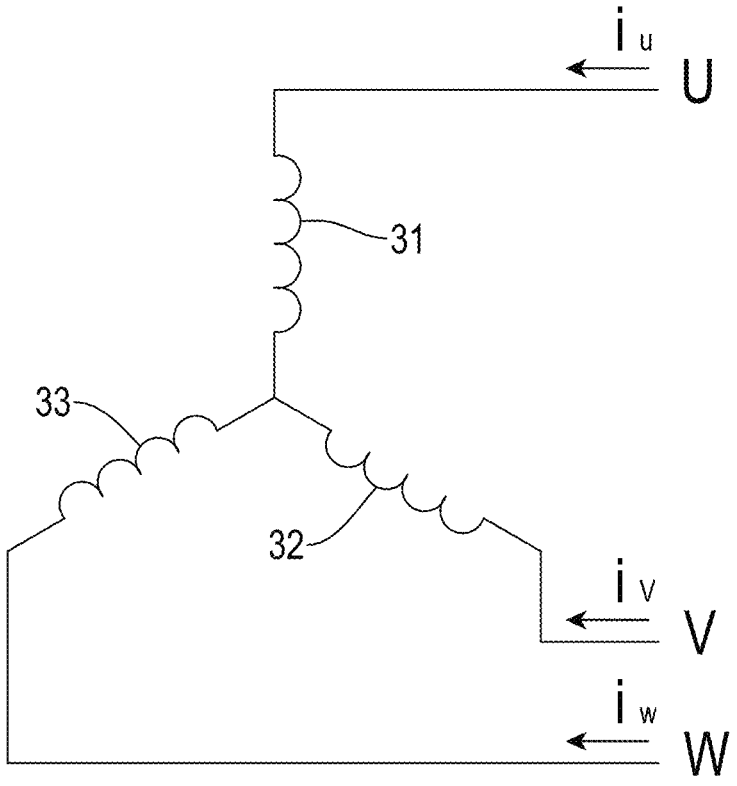


FIG.2

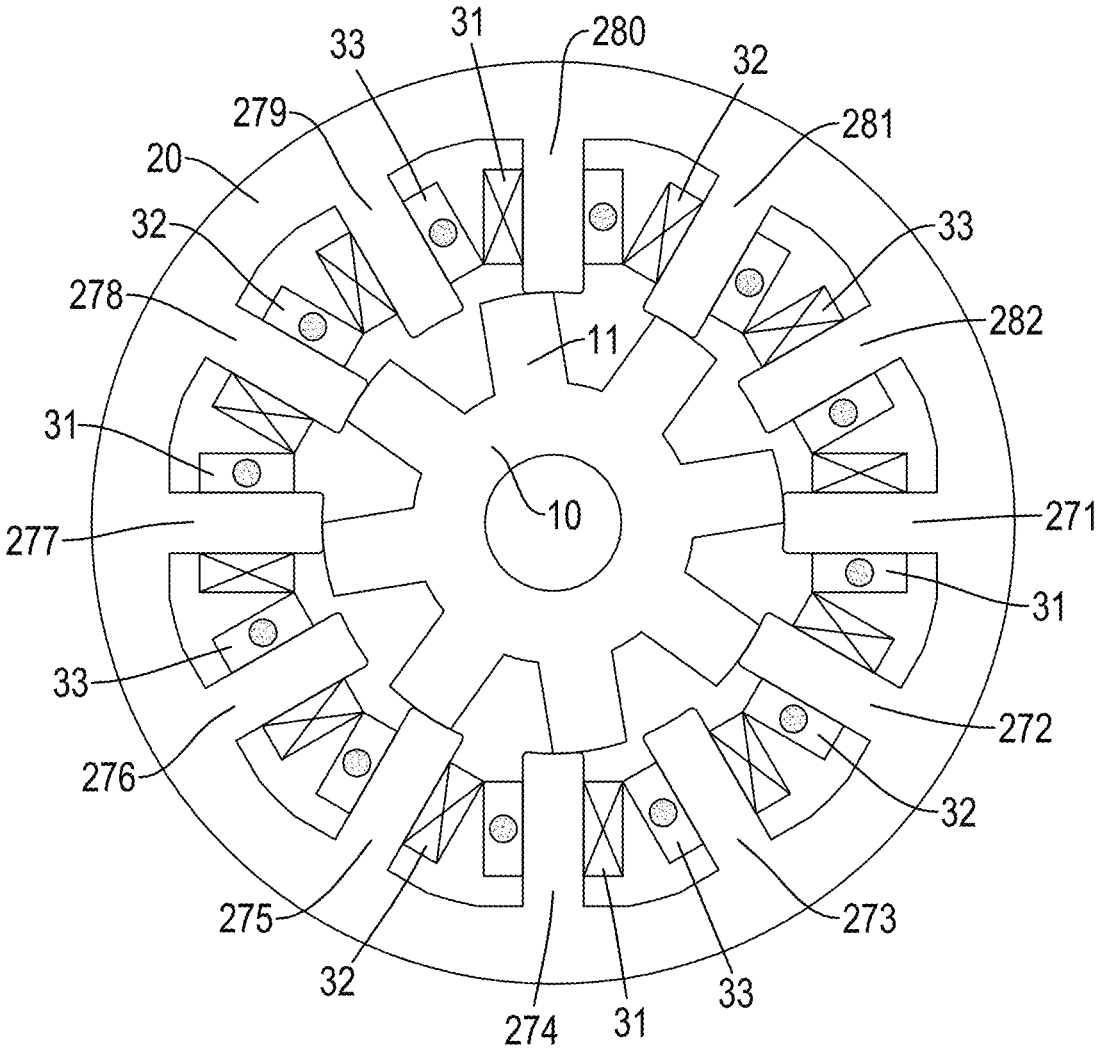

31
33
280
32
279
281
20
32
33
278
282
11
31
10
271
277
31
33
272
276
32
275
273
32
33
274
31

FIG.3

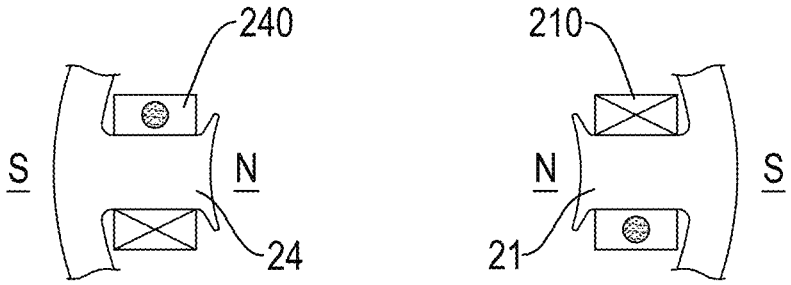


FIG.4

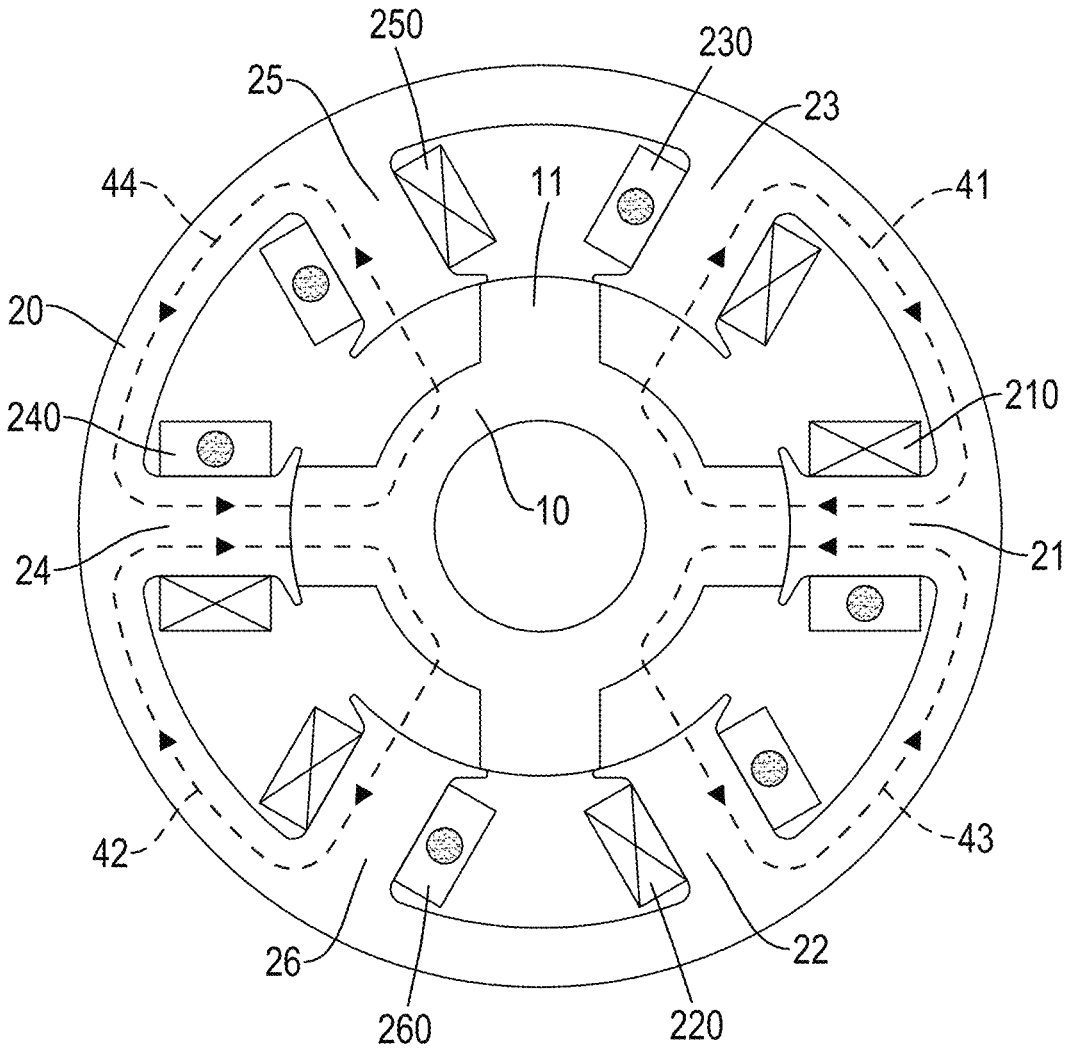


FIG.5A

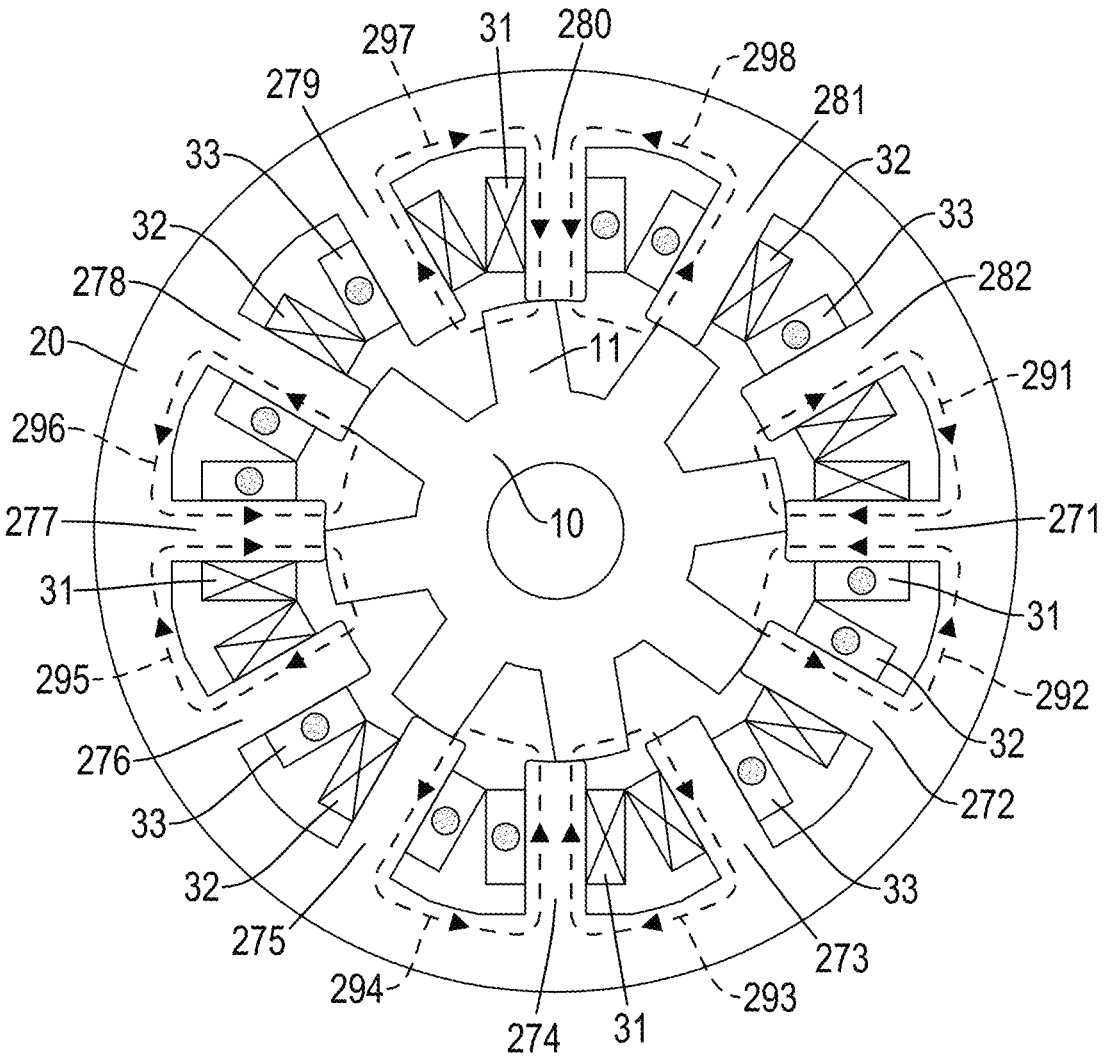

297
31
280
298
279
281
33
32
32
33
278
282
20
11
291
296
10
277
271
31
31
295
292
32
276
272
33
33
32
275
273
294
293
274
31

FIG.5B

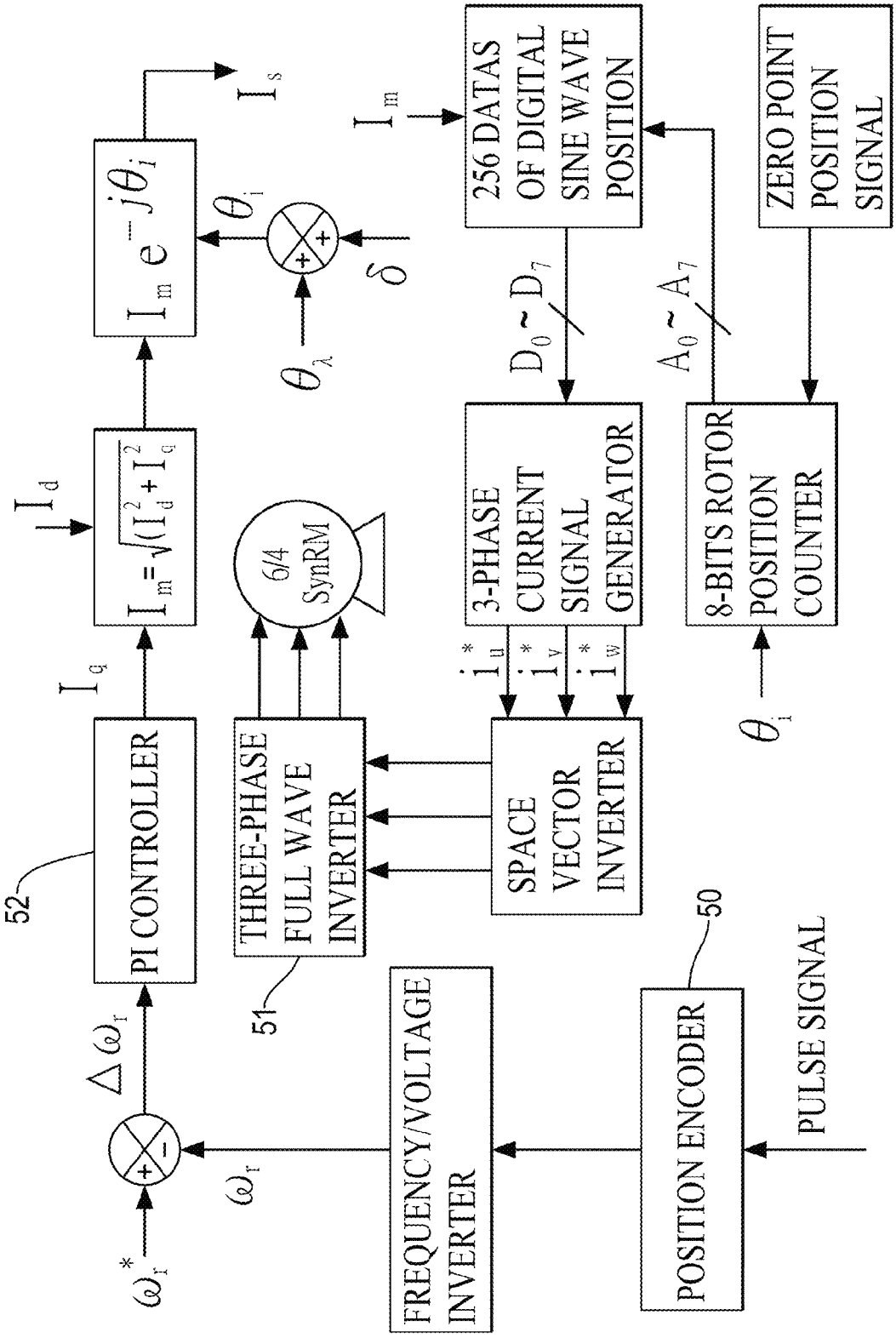

PI CONTROLLER
52
THREE-PHASE FULL WAVE INVERTER
51
6/4 SynRM
SPACE VECTOR INVERTER
3-PHASE CURRENT SIGNAL GENERATOR
256 DATAS OF DIGITAL SINE WAVE POSITION
8-BITS ROTOR POSITION COUNTER
ZERO POINT POSITION SIGNAL
FREQUENCY/VOLTAGE INVERTER
POSITION ENCODER
50
PULSE SIGNAL
ω_r^*
$\Delta\omega_r$
ω_r
I_q
I_d
$I_m = \sqrt{(I_d^2 + I_q^2)}$
$I_m e^{-j\theta_i}$
I_s
θ_i
θ_λ
δ
I_m
$D_0 \sim D_7$
$A_0 \sim A_7$
i_u^*
i_v^*
i_w^*

FIG.6

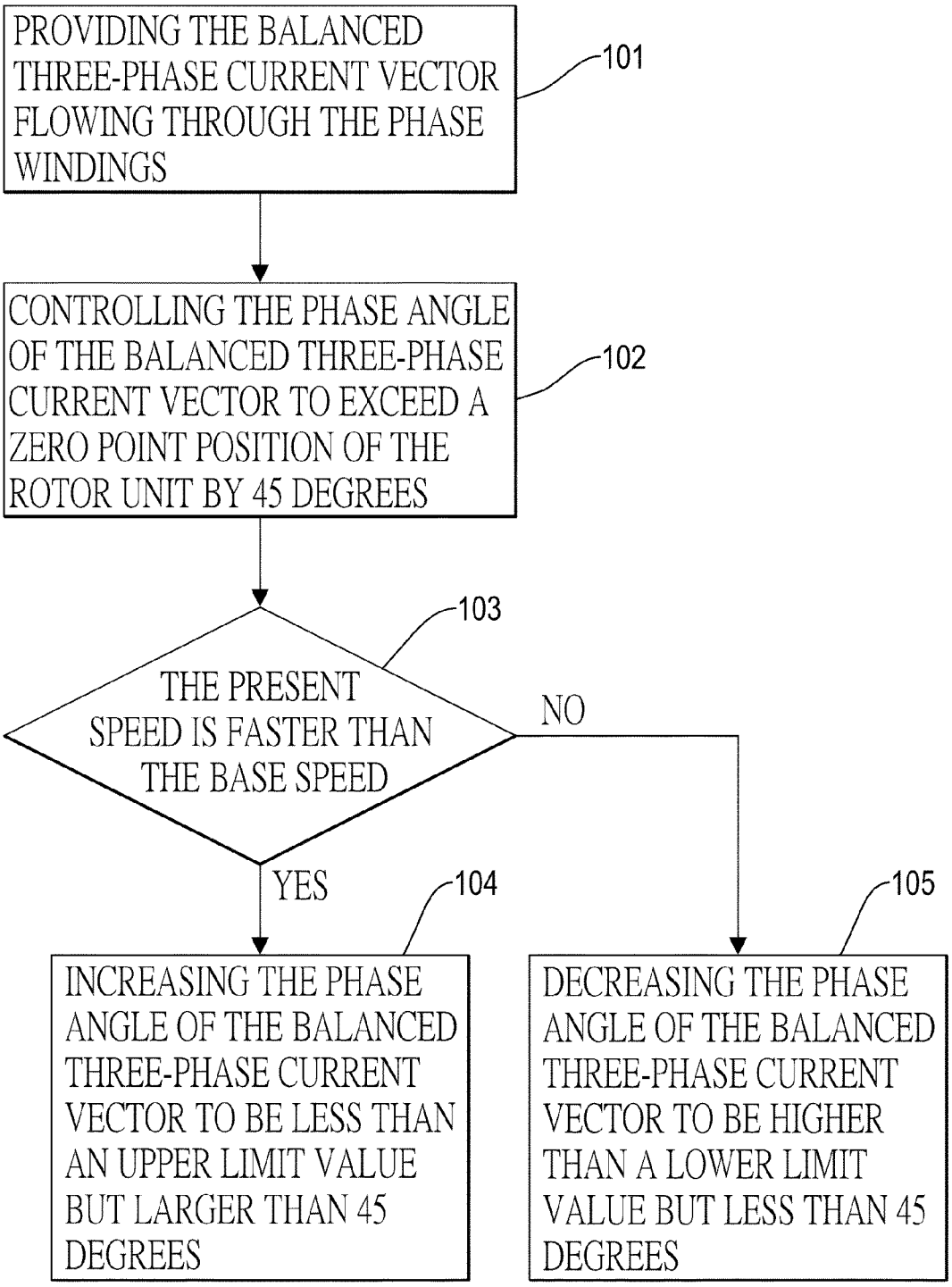

PROVIDING THE BALANCED THREE-PHASE CURRENT VECTOR FLOWING THROUGH THE PHASE WINDINGS
101
CONTROLLING THE PHASE ANGLE OF THE BALANCED THREE-PHASE CURRENT VECTOR TO EXCEED A ZERO POINT POSITION OF THE ROTOR UNIT BY 45 DEGREES
102
103
THE PRESENT SPEED IS FASTER THAN THE BASE SPEED
NO
YES
104
105
INCREASING THE PHASE ANGLE OF THE BALANCED THREE-PHASE CURRENT VECTOR TO BE LESS THAN AN UPPER LIMIT VALUE BUT LARGER THAN 45 DEGREES
DECREASING THE PHASE ANGLE OF THE BALANCED THREE-PHASE CURRENT VECTOR TO BE HIGHER THAN A LOWER LIMIT VALUE BUT LESS THAN 45 DEGREES

FIG.7

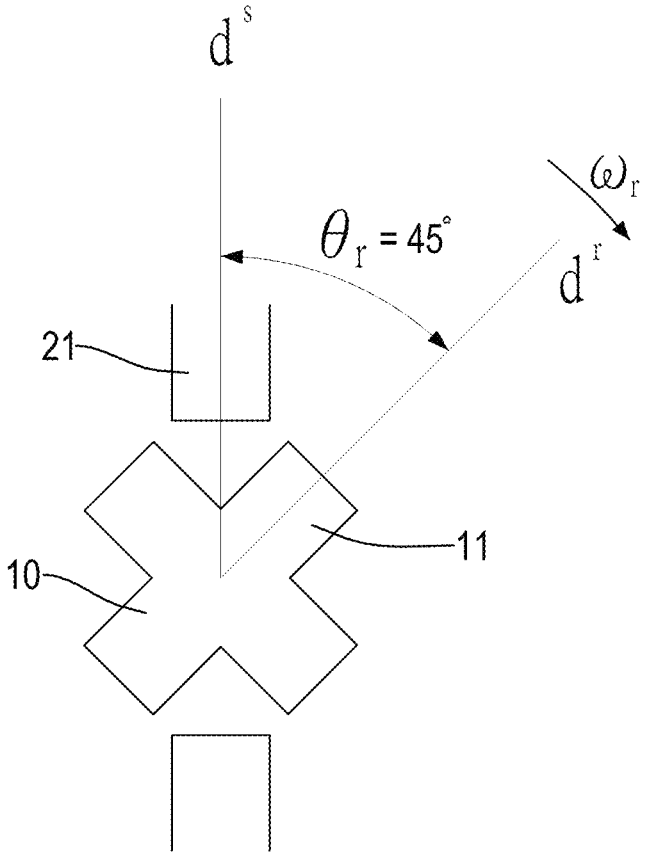


FIG.8

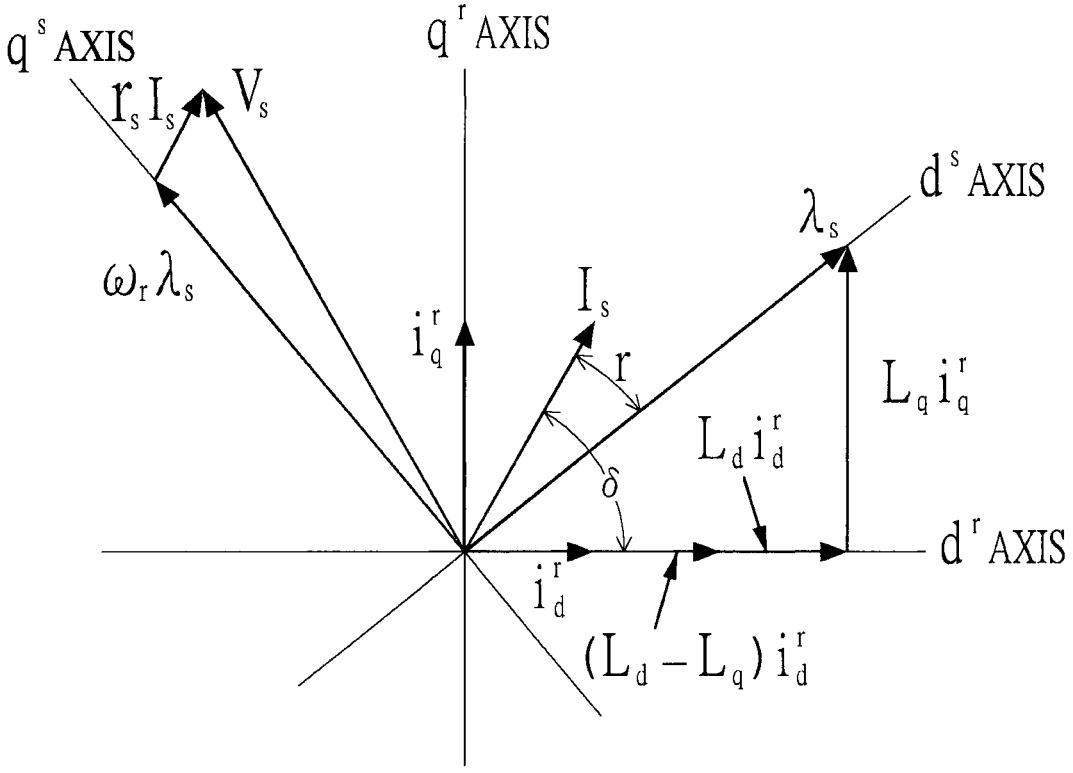

q s AXIS
r s I s
V s
ω r λ s
q r AXIS
i q r
I s
r
δ
i d r
(L d − L q) i d r
λ s
d s AXIS
L q i q r
L d i d r
d r AXIS

FIG.9

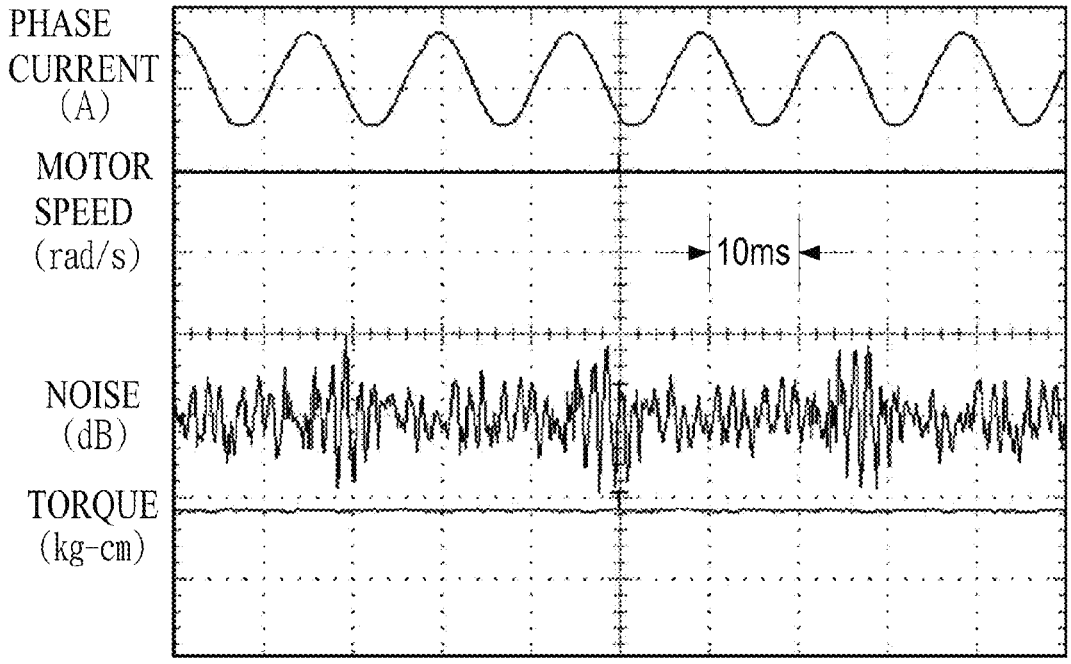


FIG.10

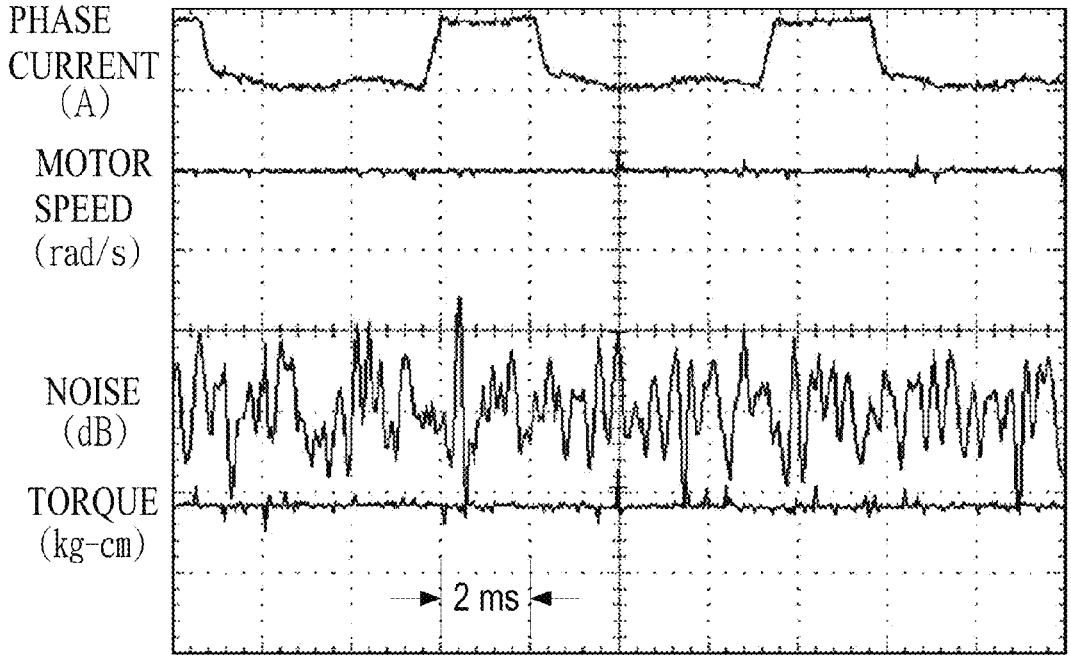


FIG.11
PRIOR ART

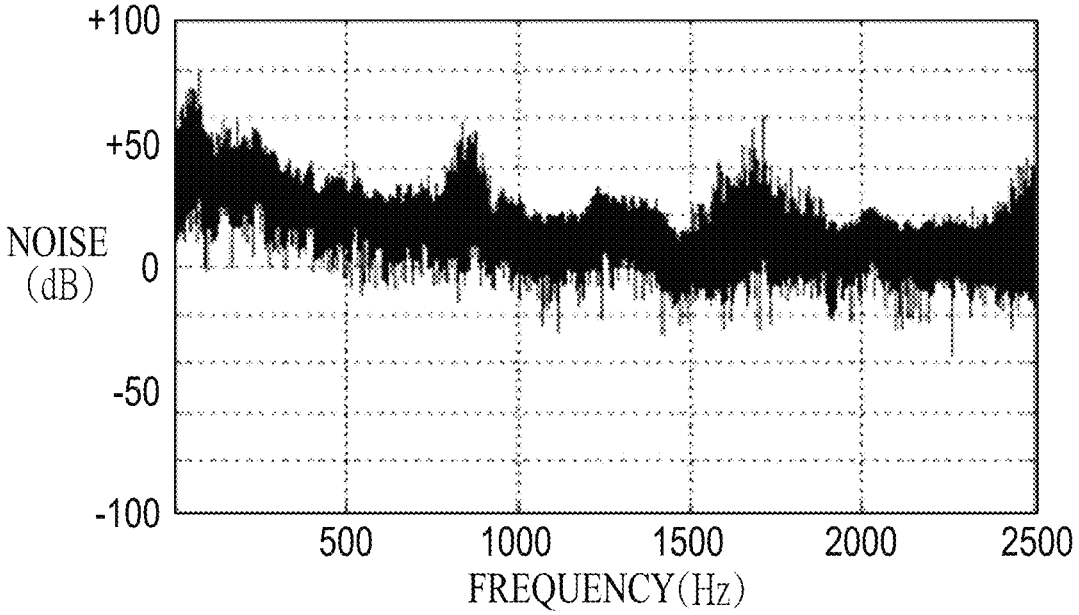


FIG.12

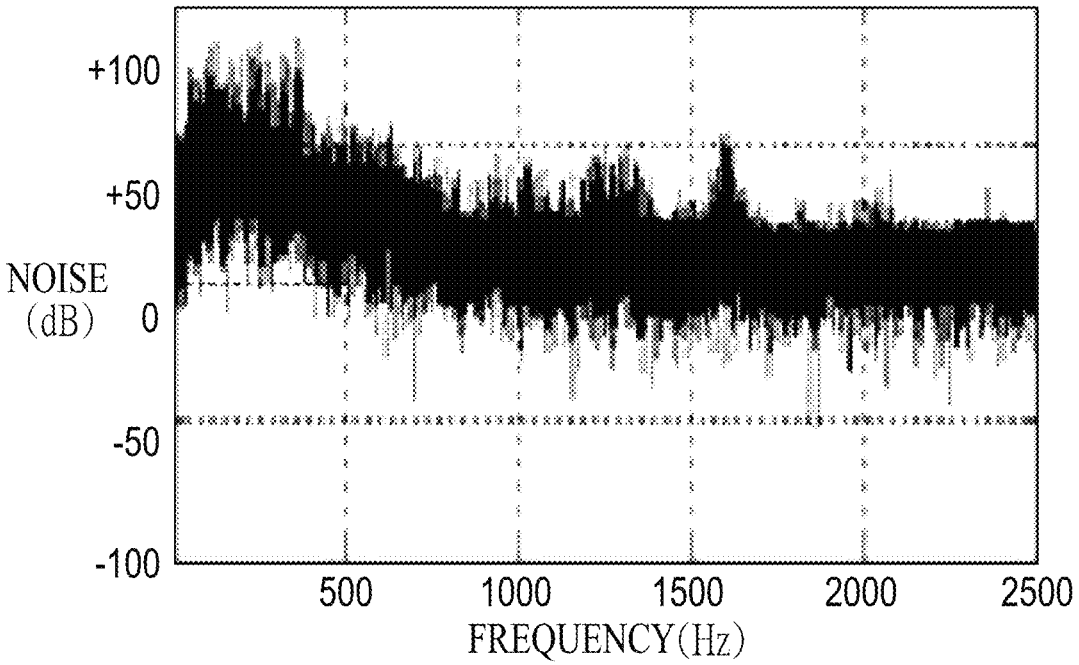


FIG.13
PRIOR ART

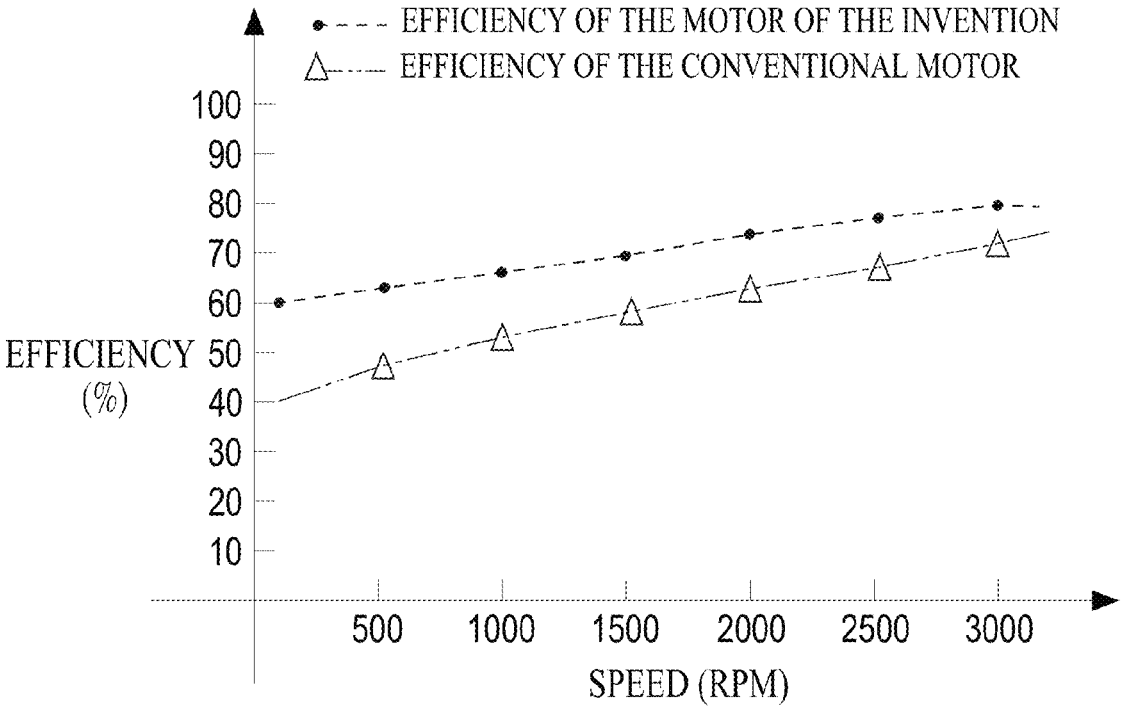

EFFICIENCY OF THE MOTOR OF THE INVENTION
EFFICIENCY OF THE CONVENTIONAL MOTOR
EFFICIENCY (%)
100
90
80
70
60
50
40
30
20
10
500
1000
1500
2000
2500
3000
SPEED (RPM)

FIG.14

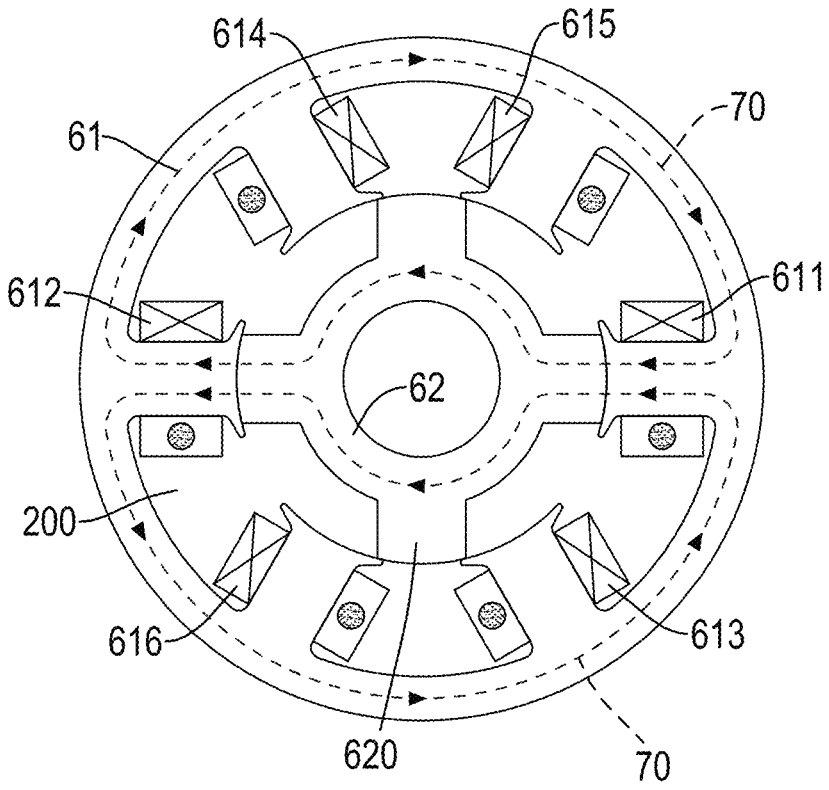


FIG.15
PRIOR ART

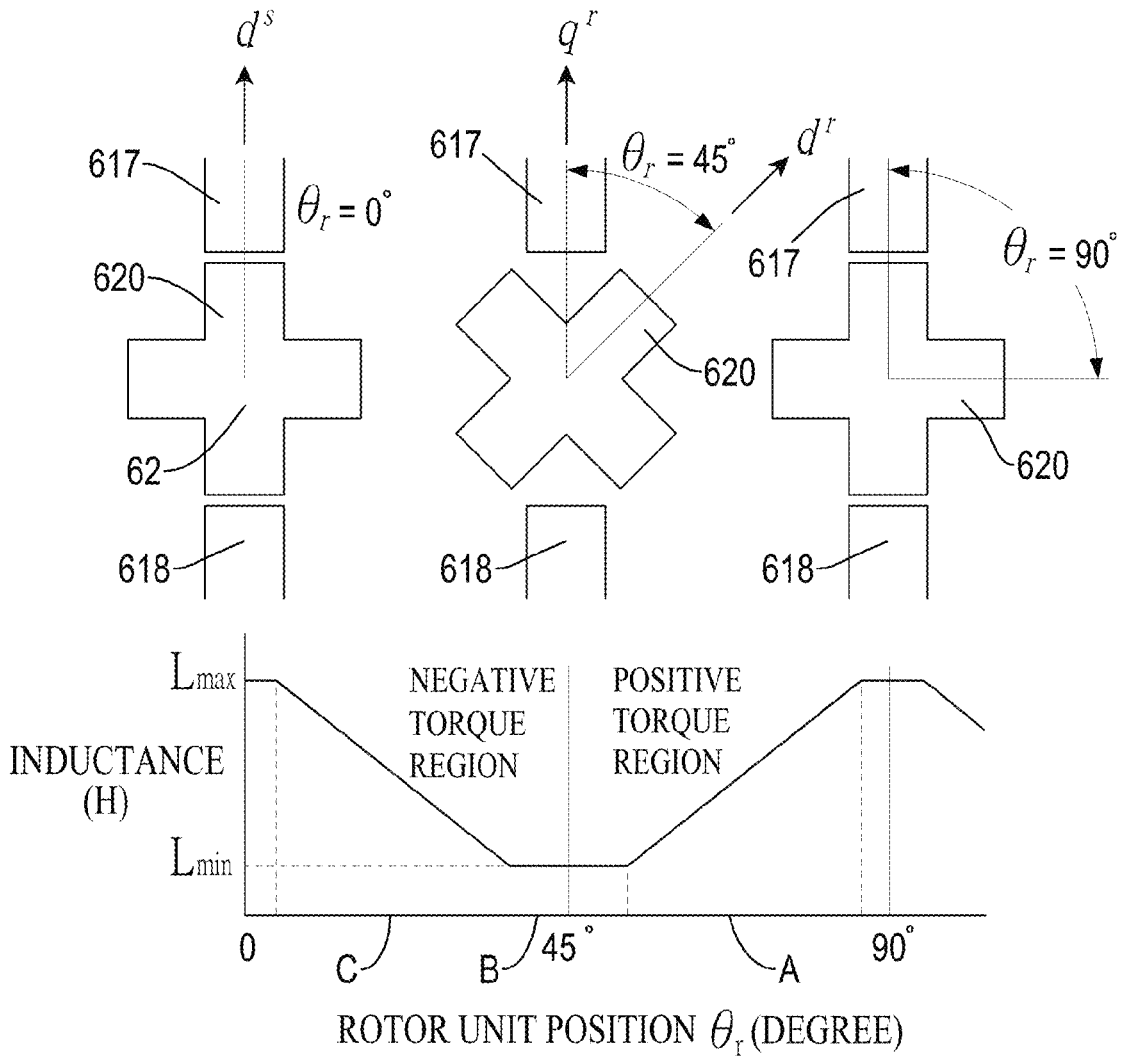


FIG.16
PRIOR ART

CONTROL METHOD FOR CONTROLLING A CURRENT VECTOR CONTROLLED SYNCHRONOUS RELUCTANCE MOTOR

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a motor, and more particularly to a current vector controlled synchronous reluctance motor and control method thereof.

2. Description of Related Art

Permanent magnet synchronous motor (PMSM) is a high efficiency motor including a stator and a rotor. The stator has multiple exciting coils for receiving a three-phase current. The rotor synchronously spins according to a rotating magnetic field generated from the exciting coils while phase currents flow through the exciting coils. However, the stator and the rotor of the PMSM are usually made of rare earth elements. The rare earth elements are expensive materials and may result in environmental pollution. Hence, to manufacture a motor without the rare earth elements is a trend nowadays.

A switched-reluctance motor is a high efficiency motor without the rare earth elements. With reference to FIG. **15**, the switched-reluctance motor has a stator **61** and a rotor **62**. The stator **61** has a U-phase coil **611**, a $\overline{U}$-phase coil **612**, a V-phase coil **613**, a $\overline{V}$-phase coil **614**, a W-phase coil **615** and a $\overline{W}$-phase coil **616**. The coils **611-616** are concentration coils and respectively have a current input terminal and a current output terminal. The rotor **62** has four poles **620**.

With reference to FIG. **15**, the symbols "⊠" and "⊡" respectively indicate the directions of phase currents flowing through the coils **611-616**. Taking a plane of FIG. **15** as a reference plane, the symbol "⊠" stands for the phase current flowing into the reference plane and the symbol "⊡" stands for the phase current flowing outward the reference plane.

As an example, the U-phase coil **611** is opposite to the $\overline{U}$-phase coil **612**. The current output terminal of the U-phase coil **611** is connected to the current input terminal of the $\overline{U}$-phase coil **612**. While a phase current is flowing through the U-phase coil **611** and the $\overline{U}$-phase coil **612**, the coils **611**, **612** induce magnetic fields in an opposite direction. For example, a magnetic pole induced by the U-phase coil **611** and adjacent to the rotor **62** is N magnetic pole. Another magnetic pole induced by the $\overline{U}$-phase coil **612** and adjacent to the rotor **62** is S magnetic pole. Closed magnetic field lines **70** are formed along the U-phase coil **611**, the rotor **62**, the $\overline{U}$-phase coil **612** and the stator **61**.

With reference to FIG. **16**, the position relationship of the poles **620** of the rotor **62** and teeth **617**, **618** of the stator **61** is disclosed. The inductance varies with a rotational angle θ, of the rotor **62**. Conventionally, a minimal inductance (L_{min}) occurs when the rotor **62** induces a maximal reluctance at a certain rotational angle θ_r. A maximal inductance (L_{max}) occurs when the rotor **62** induces a minimal reluctance at another certain rotational angle θ_r. The relationship of the rotational angle θ_r of the rotor **62** and the inductance is linear as indicated by A and B on FIG. **16**.

The switched-reluctance motor generates an electromagnetic torque T_1 according to the relationship of the rotational angle θ_r and the inductance. The electromagnetic torque T_1 can be expressed as an equation:

$$T_1 = \frac{dW_m}{d\theta_r} = \left[\frac{i_k^2 L \partial L_k(\theta_r)}{\partial \theta_r}\right] = \frac{1}{2} i_k^2 \frac{dL_k(\theta_r)}{d\theta_r},\ k = 1, 2, 3 \ldots$$

wherein k stands for a phase and

$$\frac{dL_k(\theta_r)}{d\theta_r}$$

is a phase inductance increasing ratio and can be expressed as:

$$\frac{dL_k(\theta_r)}{d\theta_r} = \begin{cases} M, & \theta_r \text{ is in the interval } A; \\ -M, & \theta_r \text{ is in the interval } B; \\ 0, & \theta_r \text{ is in the interval } C. \end{cases}$$

wherein M is a positive real constant.

However, the equations mentioned above are only adapted for a motor operating in a low speed. When the motor operates at a high speed or is connected to a load which is gradually increased, the phase inductance increasing ratio is not a constant anymore, resulting in high torque ripple and noise.

SUMMARY OF THE INVENTION

An objective of the present invention is to provide a current vector controlled synchronous reluctance motor and control method thereof. The winding rule of the phase windings and motor's control method are different from the conventional motor and the conventional method. The efficiency of the reluctance motor of the invention is improved and the noise decreases.

The synchronous reluctance motor of the invention comprises:

a rotor unit having 4×N poles, wherein N is a positive integer; and

a stator unit mounted around the rotor unit and having 6×N teeth respectively defined as a first tooth, a second tooth . . . and a $6N^{th}$ tooth; wherein

each tooth has a coil mounted thereon in a same direction to form a U-phase winding, a V-phase winding and a W-phase winding;

the U-phase winding is composed of the coils connected in series on the $3K+1^{th}$ teeth, K=0 to (2N−1);

the V-phase winding is composed of the coils connected in series on the $3K+2^{th}$ teeth, K=0 to (2N−1);

the W-phase winding is composed of the coils connected in series on the $3K+3^{th}$ teeth, K=0 to (2N−1);

the U-phase winding, the V-phase winding and the W-phase winding are connected to form a Y connection circuit;

the coils generate magnetic field lines according to a balanced three-phase current applied to the U-phase winding, the V-phase winding and the W-phase winding; in the teeth of each phase winding, the coils induce same magnetic poles; magnetic routes are formed along adjacent teeth and the rotor unit.

The method for controlling the reluctance motor including the steps of:

correspondingly providing a balanced three-phase current vector on the U-phase winding, the V-phase winding and the W-phase winding;

calibrating a zero point position of a position encoder of the rotor unit;

adjusting an amplitude and a phase angle of the balanced three-phase current vector to control the phase angle to exceed the zero point position by δ degrees according to a base speed and a rated load of the reluctance motor, wherein δ=45°;

determining whether a present speed of the reluctance motor is faster than the base speed;

increasing the phase angle of the balanced three-phase current vector when the present speed is faster than the base speed, wherein the phase angle is limited to be lower than an upper limit value but larger than 45°; and

decreasing the phase angle of the balanced three-phase current vector when the present speed is slower than the base speed, wherein the phase angle is limited to be larger than a lower limit value but less than 45°.

According to the winding rule of the coils of the invention, as an example, the amplitude of a U-phase current is maximum among a 60° commutation region. Flowing directions of a V-phase current and a W-phase current are opposite to the flowing direction of the U-phase current. Therefore, the coils of the U-phase winding on the teeth induce same magnetic poles adjacent to the rotor unit. The magnetic poles generated from the coils of the V-phase winding and the W-phase winding are opposite to the magnetic poles generated from the U-phase winding. Then two magnetic routes are respectively formed along the adjacent teeth for generating closed magnetic field lines. The magnetic route of the invention is much shorter than that of a conventional motor. As a result, the magnetic loss of the invention is less than that of the conventional motor. The efficiency of the invention is improved.

In addition, the method of the invention is to provide the balanced three-phase current to the U-phase winding, the V-phase winding and the W-phase winding synchronously, which is different from that of a conventional switched-reluctance motor. According to experiment data, the efficiency, noise performance and torque of the invention are better than those of the conventional switched-reluctance motor.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a plan view of a first embodiment (N=1) of the motor of the invention;

FIG. **2** is a circuit diagram of the U-phase winding, the V-phase winding and the W-phase winding;

FIG. **3** is a plan view of a second embodiment (N=2) of the motor of the invention;

FIG. **4** is a reference view of magnetic poles generated from the coils;

FIG. **5**A is a reference view of magnetic field lines formed in the magnetic routes of a 6/4 pole reluctance motor of the invention;

FIG. **5**B is a reference view of magnetic field lines formed in the magnetic routes of a 12/8 pole reluctance motor of the invention;

FIG. **6** is a control system block diagram executing the method of the invention;

FIG. **7** is a flow chart of the method of the invention;

FIG. **8** is a reference view of a rotational angle of the rotor unit;

FIG. **9** is a space vector diagram of the motor of the invention;

FIG. **10** is a wave diagram of a phase current, speed, noise and torque of the motor of the invention;

FIG. **11** is a wave diagram of a phase current, speed, noise and torque of a conventional motor;

FIG. **12** is a wave diagram of high frequency noise of the motor of the invention;

FIG. **13** is a wave diagram of high frequency noise of a conventional motor;

FIG. **14** is an efficiency chart of the motor of the invention and a conventional motor;

FIG. **15** is a plain view of a conventional motor; and

FIG. **16** is a reference view of a relationship of a rotor position and inductance of a conventional motor.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

With reference to FIG. **1**, the synchronous reluctance motor of this invention has a rotor unit **10** and a stator unit **20**.

The rotor unit **10** has 4×N poles **11**, wherein N is a positive integer.

The stator unit **20** is mounted around the rotor unit **10** and has 6×N teeth **21-26**. The teeth are defined as a first tooth, a second tooth . . . and a $6N^{th}$ tooth. A wire groove **200** is formed between two adjacent teeth. Multiple coils **210-260** are respectively mounted on the teeth **21-26** in a same direction as a winding rule. In this embodiment, the coils **210-260** are concentration coils. Each coil **210-260** has a head terminal and a tail terminal. The head terminal acts as a current input terminal and the tail terminal acts as a current output terminal. The tail terminal of one coil is connected to the head terminal of an opposite coil. Hence, two coils are connected to each other in series to form a phase winding.

With reference to FIG. **1**, the symbols "⊠" and "⊡" respectively indicate the directions of phase currents flowing through the coils **210-260**. Taking a plane of FIG. **1** as a reference plane, the symbol "⊠" stands for the phase current flowing into the reference plane and the symbol "⊡" stands for the phase current flowing outward the reference plane.

With reference to FIGS. **1** and **2**, each connected two coils **210-260** is respectively defined as a U-phase winding **31**, a V-phase winding **32** and a W-phase winding **33**. The phase windings **31-33** respectively receive balanced three-phase currents including a U-phase current i_u, a V-phase current i_v and a W-phase current i_w. The U-phase winding **31** is composed of the coils connected in series on the $3K+1^{th}$ teeth, K=0 to (2N−1). The V-phase winding **32** is composed of the coils connected in series on the $3K+2^{th}$ teeth, K=0 to (2N−1). The W-phase winding **33** is composed of the coils connected in series on the $3K+3^{th}$ teeth, K=0 to (2N−1). The tail terminals of the phase windings **31-33** are connected to form a Y connection circuit.

In this embodiment, N is 1. The rotor unit **10** has four poles **11**. The stator unit **20** has six teeth **21-26** defined as a first tooth **21**, a second tooth **22**, a third tooth **23**, a fourth tooth **24**, a fifth tooth **25** and a sixth tooth **26**. The U-phase winding **31** is composed of two coils **210**, **240** connected in series on the first tooth **21** and the fourth tooth **24**. The V-phase winding **32** is composed of two coils **220**, **250** connected in series on the second tooth **22** and the fifth tooth **25**. The W-phase winding **33** is composed of two coils **230**, **260** connected in series on the third tooth **23** and the sixth tooth **26**. For convenience of description, the coils **210-260** on the teeth **21-26** are respectively defined as a U-phase coil **210**, a $\overline{U}$-phase coil **240**, a V-phase coil **220**, a $\overline{V}$-phase coil **250**, a W-phase coil **230** and a $\overline{W}$-phase coil **260**. The U-phase coil **210** and the $\overline{U}$-phase coil **240** are respectively twisted on opposite teeth, such as the first tooth **21** and the fourth tooth **24**. The V-phase coil **220** and the $\overline{V}$-phase coil **250** are respectively mounted on the second tooth **22** and the fifth tooth **25**. The W-phase coil **230** and the $\overline{W}$-phase coil **260** are respectively mounted on the third tooth **23** and the sixth tooth **26**.

Similarly, with reference to FIG. **3**, a stator unit **20** of N=2 of a second embodiment is disclosed. The rotor unit **10** has eight poles **11** and the stator unit **20** has twelve teeth **271-282**. The U-phase winding **31** is composed of coils connected in series and respectively mounted on a first tooth **271**, a forth tooth **274**, a seventh tooth **277** and a tenth tooth **280**. The V-phase winding **32** is composed of coils connected in series and respectively mounted on a second tooth **272**, a fifth tooth **275**, an eighth tooth **278** and an eleventh tooth **281**. The W-phase winding **33** is composed of coils connected in series and respectively mounted on a third tooth **273**, a sixth tooth **276**, a ninth tooth **279** and a twelfth tooth **282**.

The following description takes N=1 as an example.

With reference to FIG. **2**, while the U-phase current i_u is flowing through the U-phase coil **210** and the $\overline{U}$-phase coil **240**, according to the winding rule of the coils **210**, **240**, the coils **210**, **240** induce same magnetic poles adjacent to the rotor unit **10**. With reference to FIG. **4**, the N magnetic pole induced by the U-phase coil **210** is adjacent to the rotor unit **10**. The N magnetic pole induced by the $\overline{U}$-phase coil **240** is also adjacent to the rotor unit **10**.

One period of the U-phase current i_u of the balanced three-phase currents is composed of six commutation regions, which includes 0°-60°, 60°-120°, 120°-180°, 180°-240°, 240°-300° and 300°-360°. For example, when the phase angle of the U-phase current i_u is operated among the first commutation region, such as 0°-60°, the amplitude of the U-phase current i_u is greater than that of the V-phase current i_v and the W-phase current i_w. The flowing direction of the U-phase current i_u is opposite to both the V-phase current i_v and the W-phase current i_w. With reference to FIG. **5**A, as a result, the V-phase current i_v and the W-phase current i_w induces S magnetic pole adjacent to the rotor unit **10**. A short magnetic route is formed along the first tooth **21**, the third tooth **23** and the rotor unit **10** for generating closed magnetic field lines **41**.

Similarly, a short magnetic route is formed along the forth tooth **24**, the sixth tooth **26** and the rotor unit **10** for generating closed magnetic field lines **42**. Another short magnetic route is formed along the first tooth **21**, the second tooth **22** and the rotor unit **10** for generating closed magnetic field lines **43**. Further another short magnetic route is formed along the forth tooth **24**, the fifth tooth **25** and the rotor unit **10** for generating closed magnetic field lines **44**.

In short, when the phase angle of the U-phase current i_u of the balanced three-phase currents is operated among anyone of six commutation regions, the teeth **21-26** and the rotor unit **10** generate four magnetic routes. As the magnetic fields of the windings **31-33** change, the rotor unit **10** rotates.

With reference to FIG. **5**A, the winding rule of the coils of this invention forms four magnetic routes for generating closed magnetic field lines **41-44**. Compared with the conventional magnetic route of FIG. **15**, the magnetic route of the invention is much shorter. The magnetic loss of the invention is lower than that of the conventional motor. The efficiency of the invention is improved.

The winding rule is also adapted for the second embodiment illustrated in FIG. **5**B. When the U-phase current i_w of the balanced three-phase currents is operated among anyone of the six commutation regions as mentioned above, the coils on the teeth **271-282** respectively form eight magnetic routes for respectively generating closed magnetic field lines **291-298**. For providing high power conversion efficiency, the magnetic lines in the magnetic routes are repeatedly formed according to the balanced three-phase current in every cycle, i.e. every six commutation regions.

In order to efficiently drive the reluctance motor of the invention, the present invention also provides a control method. The control method mainly adjusts an amplitude and a phase angle of the balanced three-phase current vector I_s applied to the phase windings **31-33** according to a speed (RPM) of the motor.

With reference to FIG. **6**, a control system is disclosed. A present speed ω_r and the position of the rotor unit **10** are detected by a position encoder **50**. The balanced three-phase current vector I_s is generated through a three-phase full wave inverter **51**. The balanced three-phase current vector I_s is generated based on a base speed ω_r* and a rated load. With reference to FIG. **7**, the control method of the invention is described below.

A first step of the method is to provide the balanced three-phase current vector I_s to the corresponding phase windings **31-33** (step **101**). The balanced three-phase current vector I_s includes the U-phase current i_u, the V-phase current i_v and the W-phase current i_w. The following paragraphs describe a setting rule of the balanced three-phase current vector I_s.

With reference to FIG. **8**, taking the first tooth **21** as an example, a rotational angle θ_r is defined as the angle between a central axis d^s of the first tooth **21** and a central axis d^r of the pole **11** of the rotor unit **10**.

With reference to FIG. **9**, the central axis of the first tooth **21** is defined as a d^s axis of a d^s–q^r stator coordinate system. The central axis of the pole **11** is defined as a d^r axis of a d^r–q^r rot or coordinate system. An angle difference between the d^s axis and the d^r axis is defined as θ_e, wherein

$$\theta_e = \frac{P\theta_r}{2},$$

P is a pole number. By using Clarke transformation and Park transformation, the coordinate of the first tooth **21** can be transformed to the d^r–q^r rotor coordinate system from the d^s–q^s stator coordinate system. After the coordinate transformations, the balanced three-phase current vector I_s and a counter electromotive force vector V_s can be expressed as equations (1) and (2) as below.

$$\begin{bmatrix} I_q \\ I_d \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_e & \cos\left(\theta_e - \frac{2\pi}{3}\right) & \cos\left(\theta_e + \frac{2\pi}{3}\right) \\ \sin\theta_e & \sin\left(\theta_e - \frac{2\pi}{3}\right) & \sin\left(\theta_e + \frac{2\pi}{3}\right) \end{bmatrix}\begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_e & \cos\left(\theta_e - \frac{2\pi}{3}\right) & \cos\left(\theta_e + \frac{2\pi}{3}\right) \\ \sin\theta_e & \sin\left(\theta_e - \frac{2\pi}{3}\right) & \sin\left(\theta_e + \frac{2\pi}{3}\right) \end{bmatrix}\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} \quad (2)$$

I_d stands for an exciting current. I_q stands for a torque current. I_d and I_q respectively stand for DC components of the balanced three-phase current vector I_s on the q^r axis and the d^r axis. V_d and V_q respectively stand for DC components of the counter electromotive force vector V_s.

An electric power P_e of the reluctance motor can be defined as equation (3) derived from the equations (1) and (2).

$$P_e = 3/2[V_q I_q + V_d I_d] \quad (3)$$

An electromagnetic torque T_e of the reluctance motor can be defined as equation (4) derived from the electric power P_e.

$$T_e = \frac{P_e}{\omega_r} = \frac{3/2}{\omega/(P/2)}[(\omega L_d I_d I_q - \omega L_q I_q I_d)] = \frac{3P}{4}[(L_d - L_q) I_d I_q] = \frac{3P}{4}[(L_d - L_q) I_m^2 \sin 2\delta] \quad (4)$$

P is a pole number;

ω_r is an angular frequency of the rotor unit **10** (rad/s);

ω is an operating frequency of the balanced three-phase current vector I_s;

L_q and L_d respectively stand for inductance on the q^r axis and the d^r axis of the d^r–d^r rotor coordinate system;

I_m is an amplitude of the balanced three-phase current vector I_s; and

δ is the angle formed between the balanced three-phase current vector I_s and the d^r axis in the d^r–q^r rotor coordinate system and is also defined as a torque angle.

According to the equation (4), when the torque angle is 45°, the electromagnetic torque T_e has a maximum value. The exciting current I_d, the torque current I_q, the amplitude I_m of the balanced three-phase current vector I_s and the torque angle δ satisfy the equations (5) and (6).

$$I_q = I_m \sin\delta \quad (5)$$

$$i_d = I_m \cos\delta \quad (6)$$

According to the equation (4), the electromagnetic torque T_e is determined by the inductance difference L_d–L_q, the exciting current I_d and the torque current I_q. The amplitude I_m of the balanced three-phase current vector I_s and phase angle δ can be expressed as the equations (7) and (8).

$$I_m = \sqrt{I_d^2 + I_q^2} \quad (7)$$

$$\delta = \tan^{-1}\left(\frac{I_q}{I_d}\right) \quad (8)$$

According to the equation (4), the reluctance motor of the invention can be regarded as a DC motor. The method of the invention obtains the exciting current I_d and the torque current based on the parameters (L_q, L_d, δ, etc.) of the reluctance motor. When the exciting current I_d and the torque current I_q are obtained, the balanced three-phase current vector I_s for the reluctance motor can be calculated by using an inverse-Park transformation in the d^s–q^s stator coordinate system. The balanced three-phase current vector I_s is described as the equation (9).

$$I_s = \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} = I_m \begin{bmatrix} \cos(\omega_e t) & \sin(\omega_e t) \\ \cos\left(\omega_e t - \frac{2\pi}{3}\right) & \sin\left(\omega_e t - \frac{2\pi}{3}\right) \\ \cos\left(\omega_e t + \frac{2\pi}{3}\right) & \sin\left(\omega_e t + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} I_q \\ I_d \end{bmatrix} \quad (9)$$

ω_e stands for an angular frequency of the balanced three-phase current vector I_s received by the phase windings **31-33**. According to the equations (5), (6) and (9), the balanced three-phase current vector I_s can be expressed as the equation (10).

$$I_s = \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} = I_m \begin{bmatrix} \cos(\omega_e t + \delta) & \sin(\omega_e t + \delta) \\ \cos\left(\omega_e t - \frac{2\pi}{3} + \delta\right) & \sin\left(\omega_e t - \frac{2\pi}{3} + \delta\right) \\ \cos\left(\omega_e t + \frac{2\pi}{3} + \delta\right) & \sin\left(\omega_e t + \frac{2\pi}{3} + \delta\right) \end{bmatrix} \quad (10)$$

The phase windings **31-33** receive the balanced three-phase current vector I_s as equation (10) from the three-phase full wave inverter **51**.

A current error function is defined as the equation (11).

$$\sigma = i_{sk}^*(t) - i_{sk}(t), \text{ wherein } k = u, v \text{ or } w \quad (11)$$

A current control rule for the phase windings **31-33** can be defined as below.

$$i_{sk}(t) = i_{sk}^*(t) - I_m, \text{ wherein } \sigma \le -\in, \frac{d\sigma}{dt} \le -\eta;$$

$$i_{sk}(t) = i_{sk}^*(t) + I_m, \text{ wherein } \sigma \ge +\in, \frac{d\sigma}{dt} \ge +\eta;$$

$$i_{sk}(t) = i_{sk}^*(t) - I_m\left[K_p\sigma + K_i\int \sigma dt\right],$$

$$\text{wherein } -\in \le \sigma \le +\in \quad (12)$$

i_{sk} stands for the instantaneous current in the k-phase winding;

η stands for a line current error function;

$\in$ stands for an error tolerant constant of the line current error function;

K_p stands for a selected ratio constant; and

K_i stands for a selected integral constant.

After the three-phase full wave inverter **51** provides the balanced three-phase current vector I_s to the phase windings **31-33**, the control system adjusts the amplitude and the phase angle of the balanced three-phase current vector I_s according to the base speed ω_r* and the rated load. The phase angle of the balanced three-phase current vector I_s is controlled to exceed a zero point position of the rotor unit **10** (step **102**). The control system of this invention calibrates the zero point position of the rotor unit **10** by the position encoder **50**. The zero point position of the rotor unit **10** acts as a reference point for adjusting the phase angle of the balanced three-phase current vector I_s. According to the equation (4), when the torque angle δ is 45°, it means that the phase angle of the balanced three-phase current vector I_s exceeds the zero point position of the rotor unit **10** by 45°, such that the reluctance motor can output a maximum electromagnetic torque T_e.

When the reluctance motor of the invention is working, a present speed ω_r of the reluctance motor is detected by the position encoder **50**. With reference to FIG. **6**, the control system determines whether the present speed ω_r is faster than base speed ω_r* (step **103**).

When the present speed ω_r is faster than the base speed ω_{rb}*, in order to maintain high efficiency or prevent the efficiency from decreasing, the control system of the invention gradually increases the phase angle, i.e. the torque angle δ, of the balanced three-phase current vector I_s. However, the phase angle of the balanced three-phase current vector I_s should be controlled to be larger than 45° but less than an upper limit value. In this embodiment, the upper limit value is 60° exceeding the zero point position (step **104**).

When the present speed ω_r is slower than the base speed ω_{rb}*, in order to increase the efficiency, the control system of the invention gradually decreases the phase angle, i.e. the

torque angle δ, of the balanced three-phase current vector I_s. However, the phase angle of the balanced three-phase current vector I_s should be controlled to be larger than a lower limit value but less than 45°. In this embodiment, the lower limit value is 30° exceeding the zero point position (step **105**). In conclusion, the method of the invention adjusts the phase angle of the balanced three-phase current vector I_s according to the present speed and the base speed of the reluctance motor.

With reference to FIG. **6**, the control system has a first control loop and a second control loop. The first control loop controls the electromagnetic torque T_e. The second control loop controls the speed of the reluctance motor. The control system calculates the present speed ω_r according to pulse signals generated by the position encoder **50** in a unit time. The control system calculates a speed difference $\Delta\Omega_r$ between the present speed ω_r and the base speed ω_{rb}*. A PI controller **52** then calculates the exciting current I_d and the torque current I_q using the speed difference $\Delta\omega_r$. The balanced three-phase current vector I_s is calculated according to the equations (4)-(9). Hence, the reluctance motor can output the electromagnetic torque T_e. A time-variant electromagnetic torque $T_e(t)$ of the reluctance motor can be expressed as the equation (13).

$$J\frac{d\omega_r(t)}{dt} + B\omega_r(t) + \tau_L(t) = T_e(t) \quad (13)$$

J is a rotation inertia coupled on a shaft of the motor;

B is a damping coefficient on a shaft of the motor;

ω_r is the speed of the rotor unit **10**; and

τ_L is a load torque.

The motor parameters, such as L_q, L_d and δ, can be detected or designed. The reluctance motor of the invention can be regarded as a DC motor. The DC motor satisfies the equation (4) according to the exciting current I_d and the torque current I_q. When the exciting current I_d and the torque current I_q are obtained, the control system outputs the balanced three-phase current vector I_s via the three-phase full wave inverter **51** by the Park inverse transformation according to the equations (10) and (12).

With reference to FIG. **10**, under the rated load and a base speed (2000 RPM), the noise of the reluctance motor of the invention is lower than 75 dB. The anti-noise performance of the invention is better than that of the conventional motor, wherein the anti-noise performance of the conventional motor is shown in FIG. **11**. In addition, with reference to FIGS. **10** and **11**, the torque (τ_{sf}) and speed (ω_r) of the invention are more stable than those of the conventional motor.

With reference to FIGS. **12** and **13**, it is obvious that the high frequency noise of the invention shown in FIG. **12** is lower than that of the conventional motor shown in FIG. **13**.

With reference to FIG. **14**, motor efficiencies of the motor of the invention and the conventional motor are disclosed. The broken line is an efficiency waveform of the invention. The catenary line is an efficiency waveform of the conventional motor. The efficiency of the reluctance motor of the invention is higher than the conventional motor.

What is claimed is:

1. A control method for controlling a current vector controlled synchronous reluctance motor that comprises:

a rotor unit having 4×N poles, wherein N is a positive integer; and

a stator unit mounted around the rotor unit and having 6×N teeth respectively defined as a first tooth, a second tooth . . . and a $6N^{th}$ tooth, wherein

each tooth has a coil mounted thereon in a same direction to form a U-phase winding, a V-phase winding and a W-phase winding;

the U-phase winding is composed of the coils connected in series on the $3K+1^{th}$ teeth, K=0 to (2N−1);

the V-phase winding is composed of the coils connected in series on the $3K+2^{th}$ teeth, K=0 to (2N−1);

the W-phase winding is composed of the coils connected in series on the $3K+3^{th}$ teeth, K=0 to (2N−1);

the U-phase winding, the V-phase winding and the W-phase winding are connected to form a Y connection circuit; and

the coils generate magnetic field lines according to a balanced three-phase current applied to the U-phase winding, the V-phase winding and the W-phase winding; in the teeth of each phase winding, the coils induce same magnetic poles; magnetic routes are formed along adjacent teeth and the rotor unit;

the control method including steps of:

correspondingly providing a vector of the balanced three-phase current on the U-phase winding, the V-phase winding and the W-phase winding;

calibrating a zero point position of a position encoder of the rotor unit;

adjusting an amplitude and a phase angle of the vector of the balanced three-phase current to control the phase angle to exceed the zero point position by δ degrees according to a base speed and a rated load of the reluctance motor, wherein δ=45°;

determining whether a present speed of the reluctance motor is faster than the base speed;

increasing the phase angle of the vector of the balanced three-phase current when the present speed is faster than the base speed, wherein the phase angle is limited to be less than an upper limit value but larger than 45°; and

decreasing the phase angle of the vector of the balanced three-phase current when the present speed is slower than the base speed, wherein the phase angle is limited to be larger than a lower limit value but less than 45°.

2. The control method as claimed in claim **1**, wherein:

the upper limit value exceeds the zero point position by 60 degrees; and

the lower limit value exceeds the zero point position by 30 degrees.

3. The control method as claimed in claim **2**, wherein:

the balanced three-phase current satisfies an equation of:

$$I_s = \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} = I_m \begin{bmatrix} \cos(\omega_e t + \delta) & \sin(\omega_e t + \delta) \\ \cos\left(\omega_e t - \frac{2\pi}{3} + \delta\right) & \sin\left(\omega_e t - \frac{2\pi}{3} + \delta\right) \\ \cos\left(\omega_e t + \frac{2\pi}{3} + \delta\right) & \sin\left(\omega_e t + \frac{2\pi}{3} + \delta\right) \end{bmatrix};$$

I_s is the vector of the balanced three-phase current for the stator unit;

i_u is a U-phase current flowing through the U-phase winding;

i_v is a V-phase current flowing through the V-phase winding;

i_w is a W-phase current flowing through the W-phase winding;

I_m is an amplitude of the vector of the balanced three-phase current;

ω_e is an angular frequency of the vector of the balanced three-phase current; and

δ is a torque angle between the vector of the balanced three-phase current and a d^r axis in a d^r–q^r rotor coordinate system.

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